

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization  
International Bureau



(43) International Publication Date  
7 February 2002 (07.02.2002)

PCT

(10) International Publication Number  
**WO 02/11267 A2**

(51) International Patent Classification<sup>7</sup>: **H02J 7/34**

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(21) International Application Number: PCT/US01/23681

(22) International Filing Date: 27 July 2001 (27.07.2001)

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(25) Filing Language: English

(26) Publication Language: English

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(30) Priority Data:  
60/221,596 28 July 2000 (28.07.2000) US

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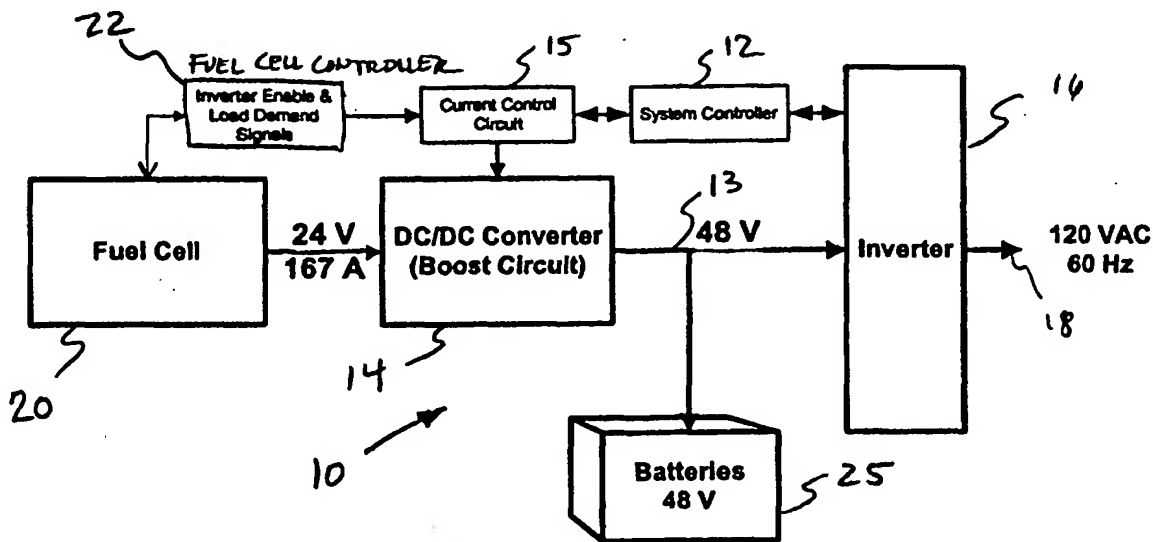
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(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

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[Continued on next page]

(54) Title: DC TO DC CONVERTER AND POWER MANAGEMENT SYSTEM



**Series Power Manager Configuration**

(57) Abstract: A DC to DC Converter includes an electrical circuit that allows batteries and other electrical energy storage devices to be charged from or to discharge to a variable voltage DC bus. This electrical circuit also enables seamless integration with other energy storage devices and/or DC power sources, such as fuel cells, to provide DC power for a Power Management System. A Power Management System preferably provides both full power source management and power conditioning. The Power Management System is able to manage power flow to and from multiple, isolated power sources and energy storage devices to deliver high quality alternating current ("AC") power to a load.

WO 02/11267 A2



**Published:**

— without international search report and to be republished upon receipt of that report

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

## 5 DC TO DC CONVERTER AND POWER MANAGEMENT SYSTEM

BACKGROUND OF THE INVENTION

This invention relates generally to systems and methods for managing direct current ("DC") power. More specifically, this invention relates to DC to DC  
10 converters and power management systems and methods.

Today, most hybrid fuel cell/battery power systems, and other systems having multiple DC power sources and batteries, are arranged as shown in FIG. 1. The arrangement shown in FIG. 1 is referred to as the "battery node" approach because the power must pass through the battery output node at the battery voltage.  
15 This configuration therefore uses battery charge controller and inverter ratings that match the capacity of the fuel cell.

Conventional DC to DC converters and their associated inverter designs and products have several deficiencies that make it difficult for them to adequately meet the functional requirements of modern hybrid power systems. These conventional  
20 converters are therefore unable to satisfy the needs of a typical energy user. Among other problems, conventional DC to DC converters typically generate electrical noise and high frequency ripple currents on the input (source) and output (load) busses. They are also poorly adapted to the regulation of input current. Furthermore, they typically exhibit energy conversion efficiencies of only around  
25 80-90%.

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SUMMARY OF THE INVENTION

According to one aspect of this invention, a DC to DC Buck and Boost Converter is provided. "Buck" power conversion refers to a reduction in voltage from an input side of the converter to an output side. "Boost" power conversion refers to an increase in voltage from the input side to the output side of the converter. According to one embodiment of this invention, the Buck and Boost DC to DC Converter includes an electrical circuit that allows batteries and other electrical energy storage devices to be charged from or to discharge to a variable voltage DC bus. This electrical circuit can also be configured to enable seamless integration with other energy storage devices and/or DC power sources, such as fuel cells, to provide DC power for a Power Management System.

Improved Boost DC to DC Converters are also provided which reduce noise and ripple currents in low voltage/high current applications. According to one embodiment, a resonant capacitance is provided by two resonant capacitors which store voltage using switches that permit zero voltage switching. According to another embodiment, an input capacitor is provided to maintain a constant voltage input to a resonant circuit. The addition of the input capacitor reduces voltage stress in a switching circuit.

A DC to DC Converter is provided in a module of a Power Management System. The Power Management System preferably provides both full power source management and power conditioning. In other words, the Power Management System preferably manages power flow to and from multiple, isolated DC power sources and energy storage devices, while delivering high quality

5 alternating current ("AC") power to a load.

### BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing features and advantages of the present invention will become more readily apparent from the following detailed description, made with reference to  
10 the following figures, in which:

FIG. 1 is a schematic block diagram of a conventional "battery node" hybrid power configuration according to the prior art.

FIG. 2 is a schematic block diagram of a series power management system configuration according to one embodiment of the present invention.

15 FIG. 3 is a schematic block diagram of a parallel power management system according to another embodiment of the present invention.

FIG. 4 is a schematic circuit diagram of a Buck and Boost DC to DC Converter according to another aspect of this invention.

20 FIG. 5A is a schematic circuit diagram of a Boost DC to DC Converter according to a further aspect of this invention.

FIG. 5B is a schematic circuit diagram of a Boost DC to DC Converter according to a still further aspect of this invention.

FIG. 5C is a schematic circuit diagram of a Boost DC to DC Converter according to the prior art.

25 FIG. 6 is a graph illustrating the current flow over time through an inductor of the Buck and Boost DC to DC converter of FIG. 4.

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DETAILED DESCRIPTION

There are presently two preferred Power Management System configurations according to this invention, including a series converter configuration, illustrated in FIG. 2, and a parallel converter configuration, shown in FIG. 3. In FIGS. 2 and 3, the hybrid power systems 10, 110 of these two  
10 embodiments are shown having only a fuel cell 20 and a battery bank 25. It should be noted, however, that the fuel cell 20 could easily be replaced by any other DC power source, by a rectified AC source, or by an energy storage unit, as desired. Similarly, the battery bank 25 could be replaced by a flywheel energy storage unit or other energy storage device that is charged with and discharges direct current. It  
15 should also be noted that any number of fuel cells 20 and DC to DC Converters 14 can be arranged in parallel to supply current to the inverter. And furthermore, the single battery bank 25 could be replaced by any number of parallel battery banks or strings connecting to the common bus.

As noted above, the schematic block diagrams in FIGS. 2 and 3 illustrate a  
20 series and a parallel Power Management System 10, 110, respectively, according to preferred embodiments of the present invention. Referring to FIGS. 2 and 3, each of the Power Management Systems 10, 110 includes three main modules: the Controller Module 12; the DC to DC Converter Module (including the current control circuit) 14, 114; and the Inverter Module 16. Any number of independent  
25 power sources, such as fuel cell 20 and battery bank 25, are also included.

The independent power sources 20, 25 can operate over different voltage ranges. The Controller Module 12 senses and analyzes the operating output of the

5 power sources 20, 25. The DC to DC Converter Module 14, 114 in conjunction with the Controller Module 12, manages and consolidates the power from these sources 20, 25 into a DC bus 13 for processing by the Inverter Module 16. The system 10, 110 delivers AC electrical power to a load through an output 18 of the Inverter Module 16. The system 10, 110 also automatically controls the charging and discharging of the battery bank 25.

The DC to DC converter 14, 114 operates with its own current control circuit 15. It also communicates with the system controller 12 and receives input signals from the fuel cell controller 22. Therefore, the terms "DC to DC Converter" and "DC to DC Buck and Boost Converter" can be used to refer to not only the actual DC to DC Converter switch related hardware, but also to the current control circuit 15 and the integration of these subsystems with the system controller 12 and the fuel cell (or photovoltaic array, or rectified AC, etc.) controller 22.

In both the series and parallel configurations, each DC bus 13 can operate at its optimum voltage. In the relatively low voltage and high current examples shown in FIGS. 2 and 3, the converter circuits 14, 114 use power MOSFETs to charge and discharge inductors to transfer power to and from the DC power sources. Both the series and parallel power management configurations 10, 110 are preferably configured to operate fully automatically between zero and full power throughput in any of their various operating modes. The transition between these modes can be seamless. Various possible modes include a first mode (e.g., Startup/Shutdown Mode) in which the battery 25 is supplying all of the power to the DC bus 13 and inverter 16; a second mode (e.g., Normal Operation Mode) in which the fuel cell 20

5 is supplying all of the power to the inverter 16; a third mode (e.g., Recharge Mode) in which the fuel cell 20 is supplying all of the power to the inverter 16 and is also charging the battery 25; and a fourth mode (e.g., Transient Mode) in which the fuel cell 20 is supplying less than the total amount of desired power to the inverter 16 and the battery 25 is supplying the balance of the power.

10 The series configured Power Management System 10, shown in FIG 2, will now be described in more detail. Referring specifically to FIG. 2, the term "series" refers to the fact that the DC to DC Converter 14 is located in series with the Fuel Cell 20 and the Inverter 16. The series configuration illustrated in FIG. 1 has an input to the inverter that is at the battery output node voltage. Unlike the  
15 conventional Hybrid Power configuration, the series Power Manager 10 includes a Controller Module 12 in addition to the DC to DC Converter Module 14 and the Inverter Module 16. The combination of these modules can be referred to as a Power Manager or Power Management System 10.

The Controller Module (or System Controller) 12 manages both the Inverter  
20 Module 16 and the Converter Module 14 to provide an integrated control system. The primary functions of the Controller Module 12 are to control the current drawn out of the fuel cell and to operate the Inverter Module 16. The Controller 12 (in combination with the DC to DC Converter 14) controls the voltage of the variable voltage DC bus. The Control Module 12 thereby provides coordinated control of  
25 the Power Management System 10. All of the modules, or subsystems, of the Power Management System 10 can be physically integrated together into a single hardware package.



5           FIG. 3 shows one possible embodiment of a parallel Power Management System configuration 110. Referring to FIG. 3, in this parallel system embodiment 110, the current control circuit 15 detects and controls the DC voltage on the buses for both the battery 25 and the power converter 114. As shown, one of the primary advantages of the parallel system 110 shown is that the voltage output from the fuel  
10 cell 20 goes directly into the inverter 16. Because only a relatively small amount of the power is required to travel through the DC to DC converter (i.e., during battery charging or transient conditions), this configuration significantly reduces losses (such as switching losses) and improves efficiency. This configuration also reduces noise and ripple currents.

15           Referring now to FIGS. 4, 5A, and 5B, three DC to DC Converter circuits 114, 214, 314, respectively, have been developed to perform the functions of the invention. Of course, many other circuit arrangements could be developed to perform the same functions and the invention is therefore not limited to any particular circuit arrangement. Circuit A, shown schematically in FIG. 4, provides a  
20 fully bi-directional buck and boost (and buck-boost) converter 114. Circuits B and C, illustrated in FIGS. 5A and 5B, respectively, are DC to DC converters 214, 314 with a boost capability only.

          Referring to FIG. 4, Circuit A consists of an "H" switch bridge having four switch and diode pairs  $S_A$  and  $D_A$ ,  $S_B$  and  $D_B$ ,  $S_C$  and  $D_C$ , and  $S_D$  and  $D_D$ , coupled to  
25 the buck/boost inductor  $L_{BB}$ . In this arrangement, the DC to DC converter 114 circuit allows both buck and boost current in both directions. This converter 114 provides a current-controlled type of converter that follows the current demanded

5 from the fuel cell by the inverter (or other load). This circuit provides excellent control of both bucking and boosting voltages with a minimum number of components.

Although FIG. 4 shows the DC to DC Converter 114 installed in series with a fuel cell 20 and inverter 16, such as in the Power Management System  
10 configuration shown in FIG. 2, because the converter can transfer power in either direction, the Circuit A converter 114 can also operate in the parallel configuration of FIG. 3. In the parallel Power Management System configuration 110 shown in FIG. 3, bi-directional buck and boost capabilities, such as those provided by this converter 114, are required. In the series configuration 10 illustrated in FIG. 2,  
15 however, only a single direction boost capability is required. Of course, many other multi-source power systems are possible which would require the fully bi-directional buck and boost capabilities of the Circuit A converter 114 or a similar converter.

FIG. 6 is a graph illustrating the current flow over time through the inductor  
20  $L_{BB}$  of Circuit A of FIG. 4. Referring to FIGS. 4 and 6, Circuit A operates as follows. When switch  $S_A$  is closed (on) and switch  $S_D$  is closed (on), current flows from the fuel cell 20 through the inductor  $L_{BB}$  to ground. The circuit remains in this state until the inductor  $L_{BB}$  is charged to a threshold voltage. This state is shown as stage 1 in FIG. 6. A voltage (or current) monitoring circuit (not shown) monitors  
25 the voltage across (or current through) the inductor  $L_{BB}$ .

Once the inductor  $L_{BB}$  has been charged to the threshold voltage, switch  $S_D$  is opened (off) and switch  $S_C$  is closed (on), while switch  $S_A$  remains closed (on).

5 This state is shown as stage 2 in FIG. 6. During this stage, current is flowing from the fuel cell 20 to the inverter 16 and battery 25. If the voltage at the output of the converter 114 (i.e., the input to the inverter 16) is raised (or boosted) above the voltage at the input of the converter 114 (i.e., the output terminal of the fuel cell 20), then the circuit is in the boost configuration. In the boost configuration, the  
10 slope of the line in FIG. 6 representing stage 2 is downward and is proportional to the voltage delta across the inductor  $L_{BB}$  (i.e., the difference between the input and output voltages), and the current through the inductor  $L_{BB}$  is being dissipated.

If the voltage at the output of the converter 114 is lower than the voltage at its input, then the circuit is in the buck configuration (i.e., voltage at the inverter  
15 input is reduced below the voltage at the fuel cell output). Current and power are still flowing from the fuel cell 20 to the inverter 16 and battery 25, but the slope of the line in FIG. 6 representing stage 2 will be upwards, again in proportion to the voltage delta across the inductor  $L_{BB}$ . In this state, the current through the inductor continues to ramp up until switch  $S_A$  is opened. The converter 114 can be kept in  
20 the buck configuration simply by cycling switch  $S_A$  to allow the current to maintain a steady level.

In the boost configuration, after the energy in the inductor  $L_{BB}$  is substantially dissipated, switch  $S_A$  is opened (off) and switches  $S_B$  and  $S_C$  are closed (on). Closing switches  $S_B$  and  $S_C$  discharges the remaining energy in the inductor  
25  $L_{BB}$  fast without stressing the two diodes  $D_B$  and  $D_C$ . At the same time, however, some current is also flowing through the diodes  $D_B$  and  $D_C$ . When the current through (or voltage across) the inductor  $L_{BB}$  drops below a threshold value (i.e.,

5 current less than 5A), switches  $S_B$  and  $S_C$  are opened (off), allowing the diodes  $D_B$  and  $D_C$  to complete the discharge of the inductor  $L_{BB}$ . Once the current through the inductor  $L_{BB}$  reaches zero, another cycle is started by closing switches  $S_A$  and  $S_D$ .

The inductor  $L_{BB}$  should be discharged after reaching the end of stage 2 before beginning a new cycle (stage 1). A current from right to left may still be  
10 passing through the inductor  $L_{BB}$  at the end of stage 2. In other words, a reverse current may still exist in the inductor  $L_{BB}$  at this point. If switches  $S_A$  and  $S_D$  were simply turned back on and switches  $S_C$  and  $S_B$  turned off, a large forward current would be generated from the fuel cell through the inductor  $L_{BB}$  to ground. These two oppositely directed currents could damage the diodes. Accordingly, the  
15 inductor  $L_{BB}$  is completely discharged before the next boost cycle is started.

It should also be noted that the converter 114 of Circuit A maintains a high current level during stage 2. This high current level increases the RMS current and eliminates the need for generating a large current peak. The bi-directional aspect of the converter 114 of Circuit A allows the inductor  $L_{BB}$  to be discharged faster (i.e.,  
20 during stages 3 and 4) between boost cycles (stages 1 and 2).

Power flow to the fuel cell 20, although not wanted in practice, is also possible using the bi-directional converter 114 of FIG. 4, and is explained here for illustration. This reverse power flow is potentially desirable for rechargeable DC power sources. Power flow to the fuel cell 20 (from right to left) is enabled in the  
25 boost configuration by closing switch  $S_C$  and cycling  $S_B$ . It is enabled in the buck configuration by cycling switch  $S_C$ . A practical application of where power flow from the inverter/battery would be desirable is where the fuel cell is replaced by a

5 second storage device such as a battery. For example, a battery bank operating at nominally 24VDC can be used to replace the fuel cell 20. In this circumstance, in the conventional direction (left to right), the DC to DC converter 114 boosts that voltage to nominally 48VDC, which is the operating voltage of the original battery bank. In the opposite direction (right to left), the DC to DC converter 114 bucks the  
10 voltage of the original battery bank to 24VDC, for instance, to recharge the battery that replaced the fuel cell.

As noted briefly above, a novel method of substantially decreasing the peak to RMS current ratio is also provided. This method is enabled, for instance, by using four parallel gate (or switch) and diode pairs. Again referring to FIGS. 4 and  
15 6, the use of four parallel gate and diode pairs allows the converter 114 of Circuit A to reduce the current peak and tailor the shape of the current flowing through the inductor  $L_{BB}$  during each cycle. This is accomplished by operating pairs of switches for the first three stages of the cycle. During stage 1, the switches  $S_A$  and  $S_D$  are on. During stage 2, the switches  $S_A$  and  $S_C$  are on. And, during stage 3, switches  $S_B$   
20 and  $S_C$  are on. During the fourth and final stage (stage 4), current is conducted through diodes  $D_B$  and  $D_C$  only. Alternatively, the cycle can be constructed of three stages rather than four, with the first two stages being the same as the first two stages described previously and with the third stage being that of conducting current through diodes  $D_B$  and  $D_C$  only. In other words, the third stage of the four stage  
25 process could be eliminated, if desired, to create a three stage process.

“Boost only” DC to DC Converter circuits 214, 314 are shown in FIGS. 5A and 5B, respectively. These converter circuits represent a significant improvement

5 to the conventional converter circuit design described in the technical paper:

Duarte, Claudio Manoel da Cunha and Ivo Barbi, "A New Family of ZVS-PSW Active- Clamping DC-to-DC Boost Converters: Analysis, Design, and Experimentation" *IEEE Transactions on Power Electronics*, Vol. 12, No. 5, September 1997, pp 824-831 (the "Duarte paper") (see FIG. 5C).

10 Circuit B, shown in FIG. 5A, and Circuit C, shown in FIG. 5B, are designed to be zero-voltage switching (ZVS) pulse-width modulation (PWM) active-clamping DC to DC boost converters. The circuits are based on the "boost-buck-boost" circuit shown in Figure 1(c) of the Duarte paper. The general circuit configuration shown in Figure 1(c) of the Duarte paper is reproduced here as FIG.  
15 5C. In each of the circuits shown in FIGS. 5A, 5B, and 5C, power is transferred to the load during a boost stage, while the clamping action is performed during a buck-boost stage. The converter circuits of FIGS. 5A, 5B, and 5C differ from earlier conventional boost pulse-width modulation (PWM) converters because of the incorporation of an additional auxiliary switch ( $S_2$ ), a resonant inductor ( $L_R$ ), a  
20 resonant capacitor ( $C_{R1}$ ) (which includes the output capacitance of the power switches), and a clamping capacitor  $C_C$ . In each of these circuits, switch  $S_1$  is the main switch. Voltage  $V_S$  is the input voltage and voltage  $V_0$  is the output voltage. Inductor  $L_R$  and capacitor  $C_{R1}$  are the resonant circuit inductor and capacitor, respectively. Inductor  $L_B$  is the boost inductor.

25 Despite the similarities between these converter circuits, the converters 214, 314 of Circuits B and C, respectively, each offer an improved design over that of the prior art circuit 414. More specifically, an additional capacitor is included in

5 each of Circuits B and C to achieving soft switching and reliable current control for low voltage (e.g., less than about 100V) and high current (e.g., up to around 150A) applications. The circuits developed and described by Duarte and Barbi are primarily aimed at high voltage (i.e., around 300V~400V), low current (i.e., around 5A) applications, and because of the low current involved, do not contemplate the  
10 need for additional capacitors for satisfactory switching. By recognizing and addressing this need, the two converters 214, 314 of FIGS. 5A and 5B are able to offer improved performance over prior art DC to DC converter circuits, such as the one 414 illustrated in FIG. 5C, in low voltage/high current applications.

Referring to FIG. 5A, the DC to DC converter 214 of Circuit B includes the  
15 addition of a capacitor  $C_{R2}$  on the output side of the resonant circuit across the auxiliary switch  $S_2$ . The second resonant capacitor  $C_{R2}$  is beneficial in low voltage and high current applications such as fuel cell and battery systems because it substantially reduces output DC current ripple and switching losses and provides better control for combined low voltage/high current applications.

20 The principle of operation of Circuit B is as follows. The inductance in the boost inductor  $L_B$  is assumed to be large enough for the inductor to act as a current source ( $I_S$ ). The clamping capacitor  $C_C$  is selected to have a large capacitance so that the voltage  $V_C$  across this capacitor can be considered a constant. The main and auxiliary switches  $S_1$  and  $S_2$ , respectively, are switched in a complementary  
25 way. The main switch  $S_1$  is turned off at time  $(t) = t_o$ , when the switching period starts.

Before time  $t_o$ , the main switch  $S_1$  is on and the auxiliary switch  $S_2$  is off.

- 5 When  $S_1$  is turned off at time  $t_0$ , the resonant capacitor  $C_{R1}$  is linearly charged, by the boost inductor current  $I_S$ , to a base voltage  $V_0$ . Due to the presence of the resonant capacitor  $C_{R1}$ , the main switch  $S_1$  is turned off with no switching loss. When the voltage  $V_{CR1}$  reaches the voltage  $V_0$ , the boost diode  $D_B$  begins conducting. The current through the resonant inductor  $L_R$  and the resonant
- 10 capacitor  $C_{R1}$  then evolves in a resonant way, and the resonant capacitor voltage  $V_{CR1}$  rises from the base voltage  $V_0$  up to a increased voltage equal to  $V_{Cc} + V_0$ . At that point, the voltages are clamped. As the capacitor voltage  $V_{CR1}$  becomes equal to  $V_{Cc} + V_0$ , the voltage across the auxiliary switch  $S_2$  is zero, and the switch  $S_2$  turns on with a no loss zero-voltage switching (ZVS). The resonant inductor  $L_R$
- 15 current then ramps down until it reaches zero, when it changes its direction and rises again.

- This stage ends when the auxiliary switch  $S_2$  is turned off with zero volts on the switch  $S_2$  due to the presence of the added capacitor  $C_{R2}$  at time  $t_3$  ( $t = t_3$ ). The voltage across the resonant capacitor  $C_{R1}$  falls, due to resonance between inductor
- 20  $L_R$  and the first or second resonant capacitor  $C_{R1}$  or  $C_{R2}$ , until it reaches zero at time  $t_4$  ( $t = t_4$ ). In stage 5, the main switch  $S_1$  is turned on without any switching losses (ZVS), because the first resonant capacitor voltage  $V_{CR1}$  became null. During this stage, the current through the resonant inductor  $L_R$  changes its polarity and ramps up to reach the boost inductor current  $I_S$ . At time  $t_5$  ( $t = t_5$ ), the diode  $D_B$  becomes
- 25 reversibly biased and power is not transferred to the load. This stage ends when the main switch  $S_1$  is turned off at the end of the first switching cycle to start the next switching cycle.



5           Circuit B offers an improvement over the prior art by splitting its resonant circuit capacitance between two capacitors  $C_{R1}$  and  $C_{R2}$  to allow zero or low voltage switching by both switches  $S_1$  and  $S_2$ . More particularly, the second resonant capacitor  $C_{R2}$  acts as part of the resonant control circuit that includes the resonant inductor  $L_R$  and the first resonant capacitor  $C_{R1}$ . The oscillation that occurs when  
10   the main switch  $S_1$  is switched on and off can be neutralized using the second capacitor  $C_{R2}$  by selectively switching the auxiliary switch  $S_2$ . When the second capacitor  $C_{R2}$  is substantially smaller than the first capacitor  $C_{R1}$ , oscillation control can be provided at low voltage. By dividing the capacitance between the two resonant circuit capacitors  $C_{R1}$  and  $C_{R2}$ , the voltage on switches  $S_1$  and  $S_2$  can be  
15   ramped down to allow zero voltage switching. Furthermore, because the capacitors store the voltages with no voltage losses, they provide efficient power transfer between the input and the output nodes of the converter 214.

Referring now to FIG. 5B, the DC to DC converter 314 of Circuit C is another boost converter embodiment capable of use in the Power Management  
20   System 10 of FIG. 2. In this converter 314, an input capacitor  $C_1$  has been added to the input side of the resonant circuit of the prior art converter 414 of FIG. 5C. Without the capacitor  $C_1$ , the voltage at node A dips in high current applications, and large voltage swings occur at that node. These voltage swings cause a large voltage stress on switch  $S_1$  and result in an inability to achieve reliable control of  
25   the current through the resonant inductor  $L_R$ .

With the addition of capacitor  $C_1$  in the circuit, the voltage at node A can be held steady during switching. Because the input capacitor  $C_1$  maintains a constant

5 voltage at node A, the voltage stress on the main switch  $S_1$  is reduced. Specifically, by dampening the voltage swings at node A, the input capacitor  $C_1$  filters out high voltage swings and keeps them from affecting the switch  $S_1$ . This steady voltage at node A helps achieve soft switching and good current control.

Having described and illustrated the principles of the invention in various  
10 preferred embodiments thereof, it should be apparent that the various implementations of the invention described above can be modified in arrangement and detail without departing from such principles. We claim all modifications and variations coming within the spirit and scope of the following claims.

5

CLAIMSWhat is Claimed is:

1. A power management system, comprising:  
a plurality of independent DC power sources connected to a DC bus;  
10 a DC to DC converter connected between an output of one or more of the  
DC power sources and the DC bus; and  
a system controller for managing power transfer between the multiple  
independent DC power sources and the DC bus.
- 15 2. A power management system according to claim 1, wherein at least one of  
the independent power sources comprises a rechargeable DC power source for  
supplying power to and receiving power from the DC bus.
3. A power management system according to claim 1, wherein the system  
20 controller is configured to control the current supplied from each of the power  
sources to the DC bus and from the DC bus to the power sources.
4. A power management system according to claim 1, further comprising an  
inverter for converting DC power from the independent DC power sources into AC  
25 power.

5     5.     A power management system according to claim 1, wherein at least one of  
the independent DC power sources comprises a fuel cell having a fuel cell  
controller.

6.     A power management system according to claim 5, wherein the system  
10     controller communicates with the fuel cell controller to control the amount of power  
supplied by the fuel cell to the DC bus.

7.     A power management system according to claim 1, wherein the DC to DC  
converter further comprises a converter control circuit that communicates with the  
15     system controller to control an amount of power transferred between the DC to DC  
converter and the DC bus.

8.     A power management system according to claim 1, further comprising an  
inverter, wherein at least one of the independent DC power sources comprises a fuel  
20     cell, and wherein the DC to DC converter is arranged in series between the fuel cell  
and the inverter.

9.     A power management system according to claim 1, further comprising an  
inverter, wherein at least one of the independent DC power sources comprises a fuel  
25     cell, and wherein the DC to DC converter is arranged in parallel with the fuel cell  
and the inverter.

5 10. A method for managing multiple independent DC power sources,  
comprising:

arranging a plurality of independent DC power sources in communication  
with a DC bus;

10 converting a voltage from one or more of the independent DC power sources  
to conform to a voltage of the DC bus; and  
controlling the amount of power that the DC bus supplies to or receives  
from one or more of the independent power sources.

11. A method of managing multiple independent DC power sources according  
15 to claim 10, wherein controlling the amount of power that the DC bus supplies to or  
receives from one or more of the independent power sources comprises integrating  
between a plurality of modes wherein each of the DC power sources is either  
supplying some or all of the required power, being recharged by one or more of the  
other DC power sources, or being isolated from the DC bus.

20

12. A method of managing multiple independent DC power sources according  
to claim 10, wherein at least one of the DC power sources comprises a fuel cell, and  
wherein converting a voltage from one or more of the independent DC power  
sources to conform to a voltage of the DC bus comprises arranging a DC to DC  
25 converter in series between the fuel cell and the DC bus.

5 13. A method of managing multiple independent DC power sources according to claim 10, wherein at least one of the DC power sources comprises a fuel cell, and wherein converting a voltage from one or more of the independent DC power sources to conform to a voltage of the DC bus comprises arranging a DC to DC converter in parallel with the fuel cell.

10

14. A method of managing multiple independent DC power sources according to claim 10, further comprising supplying the DC power from the DC bus to an inverter for conversion into AC power to enable the provision of AC power to a load.

15

15. A DC to DC converter, comprising:  
an input node for receiving power from a DC power source;  
a plurality of switch-diode pairs arranged between the input node and an  
20 output node; and

an inductor arranged between two or more of the switch-diode pairs,  
wherein the inductor is configured to convert a voltage between the input node and the output node in response to actuation of the switches.

25 16. A DC to DC converter according to claim 15, wherein the plurality of switch-diode pairs comprises four switch-diode pairs, and wherein two switch-diode pairs are connected on each side of the inductor.

5 17. A DC to DC converter according to claim 15, wherein current through the inductor is fully bi-directional.

18. A DC to DC converter according to claim 15, wherein a first switch-diode pair is connected between the input node and a first end of the inductor, and  
10 wherein a second switch-diode pair is connected between the first end of the inductor and ground.

19. A DC to DC converter according to claim 15, wherein a third switch-diode pair is connected between a second end of the inductor and the output node, and  
15 wherein a fourth switch-diode pair is connected between the second end of the inductor and ground.

20. An improved DC to DC converter having a boosting inductor connected to an input node, a clamping capacitor, a plurality of diodes, and a resonant circuit  
20 comprising a resonant inductor and a resonant capacitor, wherein the improvement comprises an additional capacitor configured to stabilize a voltage.

21. An improved DC to DC converter according to claim 20, wherein the node comprises an input node to the resonant circuit.

25

22. An improved DC to DC converter according to claim 20, wherein the node comprises an output node from the resonant circuit.

5     23.     A method of reducing a peak to RMS current ratio through an inductor of a converter, the method comprising:

switching a first one or more switches of the converter to an on position to provide a current flow through the inductor;

switching a second one or more switches of the converter to an on position  
10     to supply the current flow to a load; and  
allowing the current flow through the inductor to dissipate.

24.     A method of reducing a peak to RMS current ratio according to claim 23, wherein allowing the current through the inductor to dissipate comprises switching  
15     a third one or more switches of the converter to an on position.

25.     A method of reducing a peak to RMS current ratio according to claim 23, wherein allowing the current through the inductor to dissipate comprises switching all of the switches to an off position to permit current to dissipate through one or  
20     more diodes of the converter.

26.     A method of reducing a peak to RMS current ratio according to claim 23, wherein the converter comprises a plurality of switch-diode pairs, and wherein:  
switching a first one or more switches of the converter to an on position to  
25     provide a current flow through the inductor comprises switching a first and a fourth switch to an on position; and  
switching a second one or more switches of the converter to an on position



5 to supply the current flow to a load comprises switching a third switch to an on position and the fourth switch to an off position.

27. A method of reducing a peak to RMS current ratio according to claim 26, wherein allowing the current flow through the inductor to dissipate comprises  
10 closing a second switch and opening the third switch.

28. A method of reducing a peak to RMS current ratio according to claim 26, wherein allowing the current flow through the inductor to dissipate comprises opening all of the switches to allow the current flow to dissipate through one or  
15 more of the diodes.

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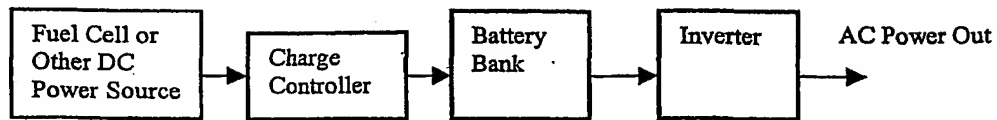


FIG. 1  
(Prior Art)

Typical "Battery Node" Hybrid Power Configuration

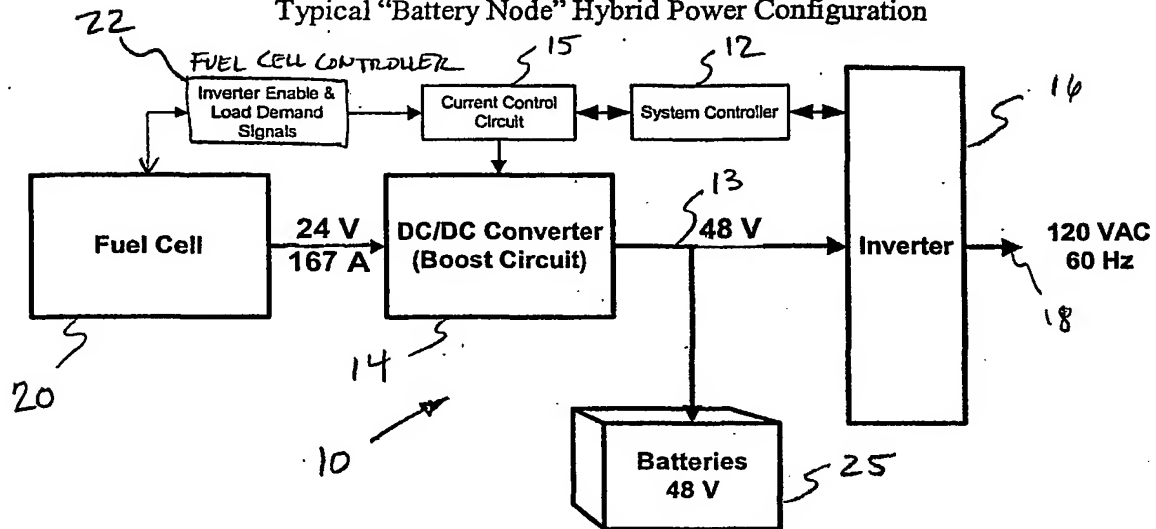


FIG. 2

Series Power Manager Configuration

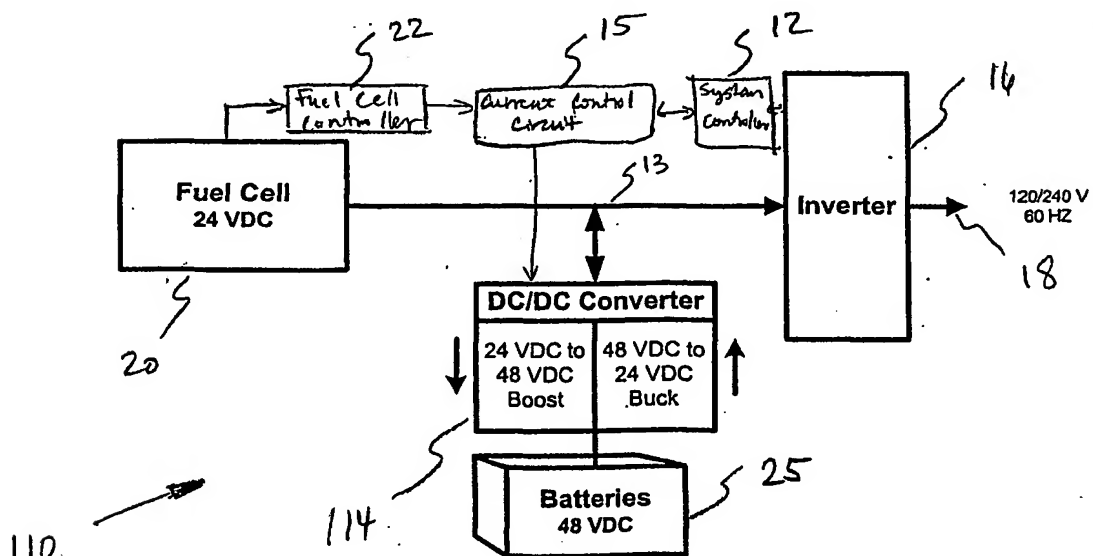


FIG. 3

Parallel Power Manager Configuration

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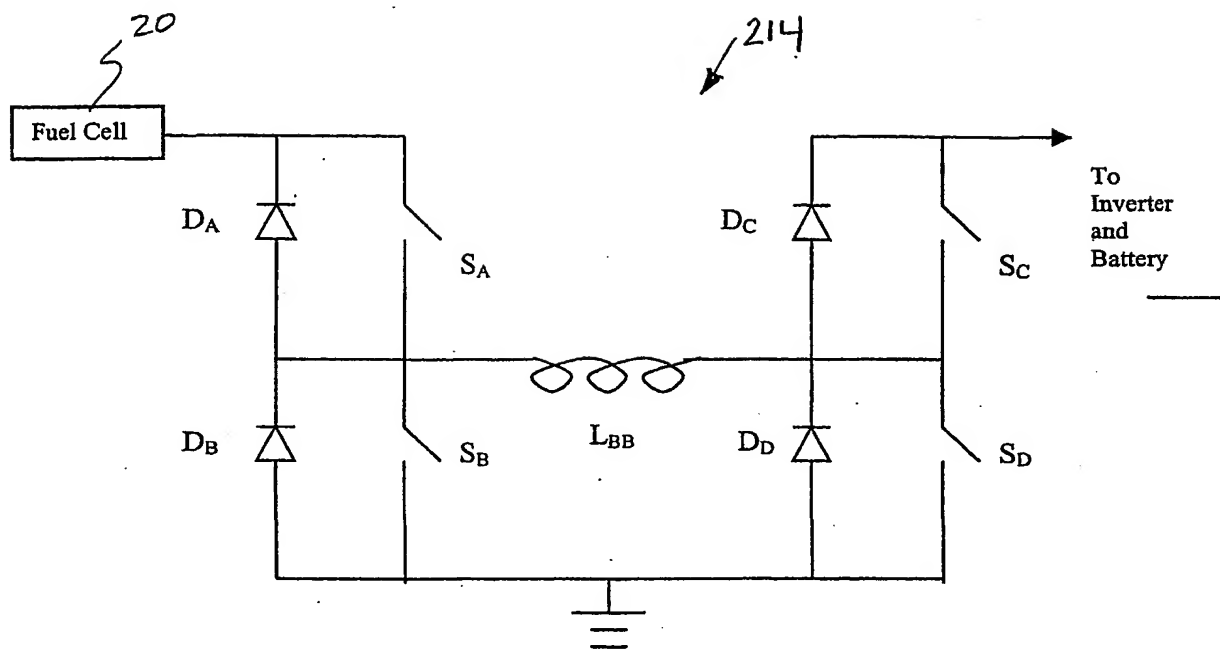


FIG. 4

Circuit A - Buck and Boost DC to DC Converter

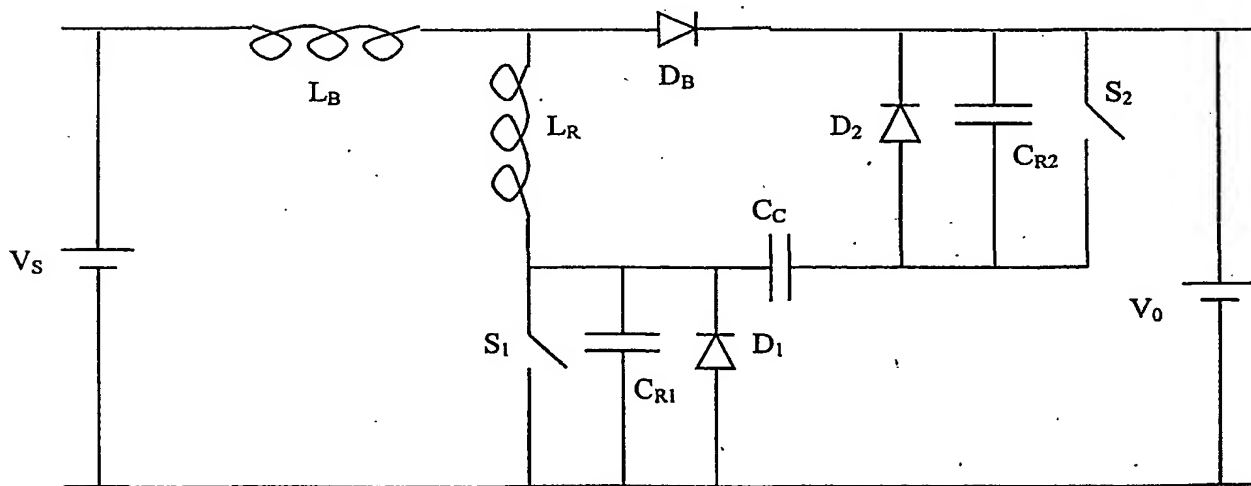


FIG. 5A

Circuit B - Boost DC to DC Converter with Capacitor  $C_{R2}$

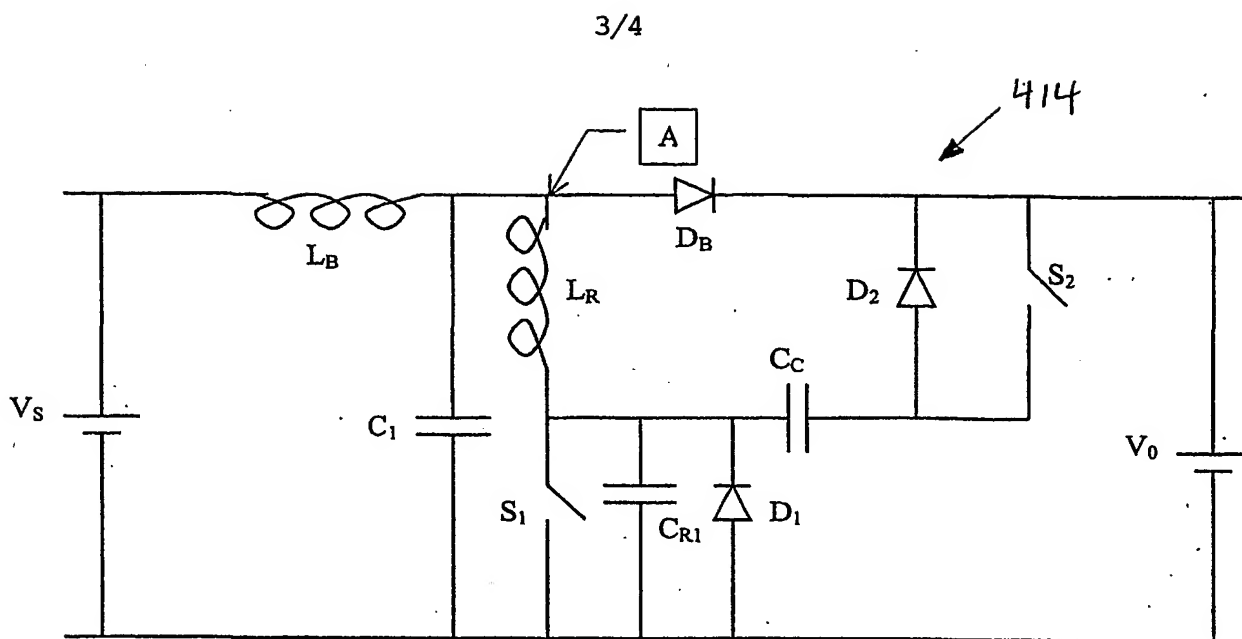


FIG. 5B  
Circuit C - Boost DC to DC Converter with Capacitor  $C_1$

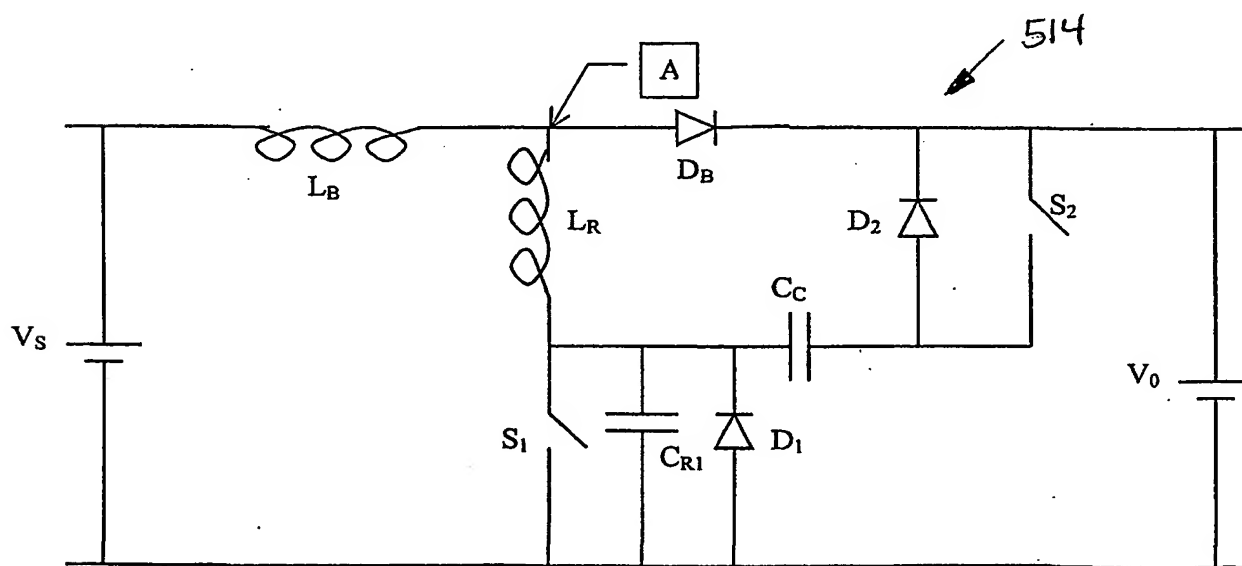


FIG. 5C  
(Prior Art)  
Duarte and Barbi - Boost DC to DC Converter

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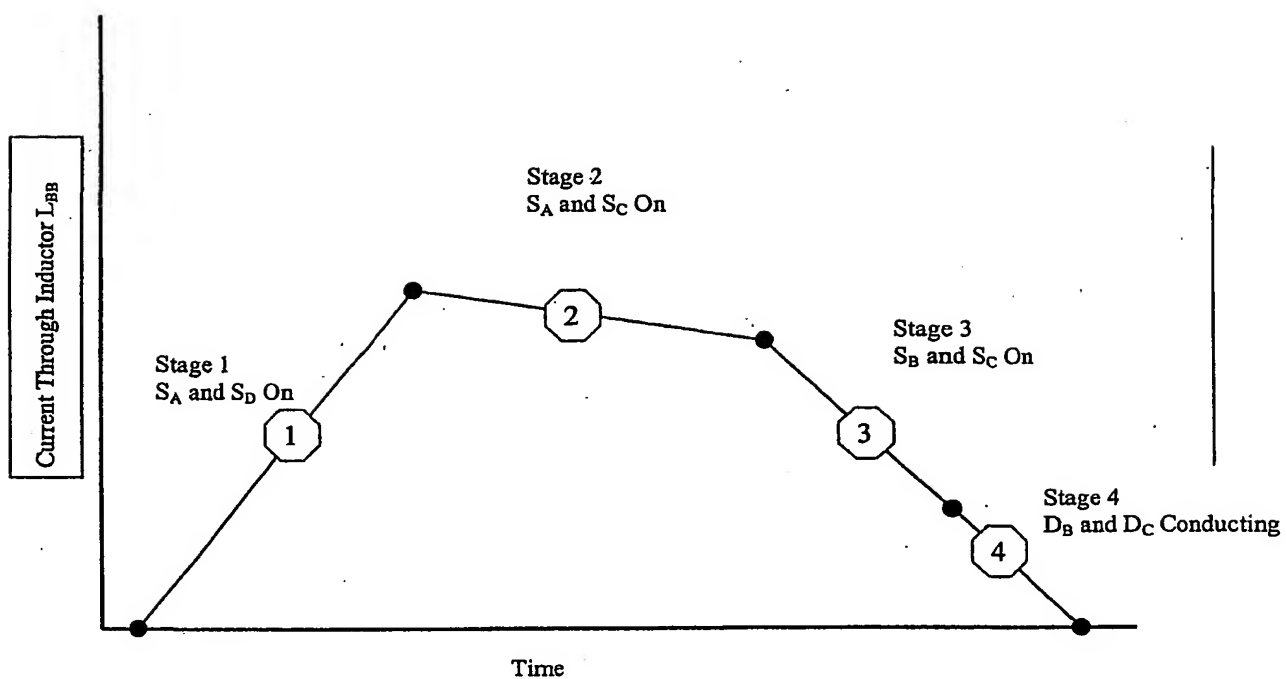


FIG. 6

Current Through Inductor  $L_{BB}$  Versus Time for One Cycle of Operation of Circuit A

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(19) World Intellectual Property  
Organization  
International Bureau



(43) International Publication Date  
7 February 2002 (07.02.2002)

PCT

(10) International Publication Number  
**WO 2002/011267 A3**

(51) International Patent Classification<sup>7</sup>: **H02J 7/34**,  
H02M 3/158

(21) International Application Number:  
PCT/US2001/023681

(22) International Filing Date: 27 July 2001 (27.07.2001)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:  
60/221,596 28 July 2000 (28.07.2000) US

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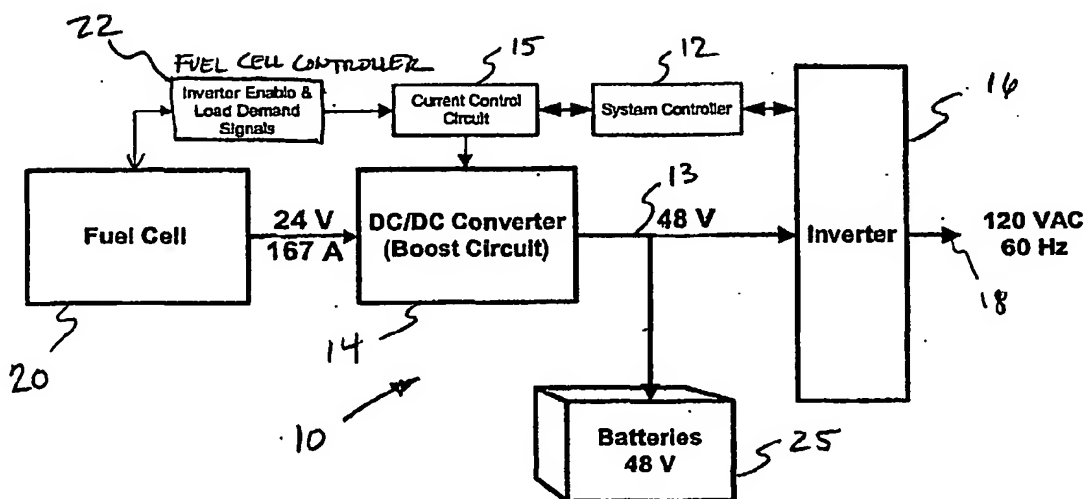
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(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, TR), OAPI patent (BF, BJ, CF,

[Continued on next page]

(54) Title: DC TO DC CONVERTER AND POWER MANAGEMENT SYSTEM



Series Power Manager Configuration

(57) Abstract: A DC to DC Converter (14, 114) includes an electrical circuit that allows batteries and other electrical energy storage devices to be charged from or to discharge to a variable voltage DC bus (13). This electrical circuit also enables seamless integration with other energy storage devices and/or DC power sources, such as fuel cells (20), to provide DC power for a Power Management System. A Power Management System preferably provides both full power source management and power conditioning. The Power Management System is able to manage power flow to and from multiple, isolated power sources and energy storage devices to deliver high quality alternating current ("AC") power to a load.

WO 2002/011267 A3



CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

(88) Date of publication of the international search report:

6 May 2004

**Published:**

— with international search report

*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*



## INTERNATIONAL SEARCH REPORT

National Application No  
PCT/US 01/23681A. CLASSIFICATION OF SUBJECT MATTER  
IPC 7 H02J7/34 H02M3/158

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)  
IPC 7 H02J H02M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)  
EPO-Internal

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 334 463 A (SHINDO KOJI ET AL) 2 August 1994 (1994-08-02) abstract column 5, line 8 figure 1	1-8, 10-12, 14
X	DE 198 10 468 A (DAIMLER CHRYSLER AG) 16 September 1999 (1999-09-16)  column 3 -column 4 figure 3  --- -/--	1-5, 9-11, 13, 14

☒ Further documents are listed in the continuation of box C.☒ Patent family members are listed in annex.

## \* Special categories of cited documents:

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- \*O\* document referring to an oral disclosure, use, exhibition or other means
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Date of the actual completion of the international search

28 June 2002

Date of mailing of the international search report

28 JUN 2002

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## INTERNATIONAL SEARCH REPORT

International Application No

PCT/US 01/23681

## C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 5 714 874 A (PIER BONNEFOY) 3 February 1998 (1998-02-03) abstract  paragraph '000I! page 287; figure 2 column 2, line 46 - line 62 ----	1-3, 10, 11 4-9, 12-14
X Y	US 5 734 258 A (ESSER ALBERT ANDREAS MARIA) 31 March 1998 (1998-03-31)  column 4, line 40 - line 67 column 5, line 1 - line 34 figures 1, 3A, 6 ----	15-19, 23, 24, 26, 27 20-22
X	CARICCHI F ET AL: "Study of bi-directional buck-boost converter topologies for application in electrical vehicle motor drives" APPLIED POWER ELECTRONICS CONFERENCE AND EXPOSITION, 1998. APEC '98. CONFERENCE PROCEEDINGS 1998., THIRTEENTH ANNUAL ANAHEIM, CA, USA 15-19 FEB. 1998, NEW YORK, NY, USA, IEEE, US, 15 February 1998 (1998-02-15), pages 287-293, XP010263608 ISBN: 0-7803-4340-9 paragraph '000I! page 287; figure 2 ----	15-19
Y	C M DA CUNHA DUARTE, I BARBI: "A new family of ZVS-PWM active clamping DC-to-DC boost converters: analysis, Design and Experimentation" IEE TRANSACTION ON POWER ELECTRONICS, vol. 12, no. 5, September 1997 (1997-09), pages 824-831, XP002203819 cited in the application abstract figure 1C -----	20-22

# INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US 01/23681

## Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This International Search Report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:  
because they relate to subject matter not required to be searched by this Authority, namely:
  
2. ☐ Claims Nos.:  
because they relate to parts of the International Application that do not comply with the prescribed requirements to such an extent that no meaningful International Search can be carried out, specifically:
  
3. ☐ Claims Nos.:  
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

## Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this International Search Report covers all searchable claims.
  
2. ☒ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
  
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this International Search Report covers only those claims for which fees were paid, specifically claims Nos.:
  
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this International Search Report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☐ No protest accompanied the payment of additional search fees.

## FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. Claims: 15-28

A DC-DC converter comprising: an input node for receiving power from a DC power source, a plurality of diode-switch pairs, an inductor configured to convert a voltage between the input and the output node in response to actuation of the switches and relative method of operation.

and

A DC-DC converter having a boosting inductor connected to an input node, a campling capacitor, a plurality of diodes, and a resonnat circuit comprising a resonant inductor and a resonant capacitor, and an additional capacitor configured to stabilize a voltage.

The attention of the applicant has to be drawn to the fact that even if claims 20-22 have been searched, two inventions are present in this set of claims, namely:

1.1. Claims: 15-19, 23-28

A DC-DC converter comprising: an input node for receiving power from a DC power source, a plurality of diode-switch pairs, an inductor configured to convert a voltage between the input and the output node in response to actuation of the switches and relative method of operation.

1.2. Claims: 20-22

A DC-DC converter having a boosting inductor connected to an input node, a campling capacitor, a plurality of diodes, and a resonnat circuit comprising a resonant inductor and a resonant capacitor, and an additional capacitor configured to stabilize a voltage.

Please note that all inventions mentioned under item 1, although not necessarily linked by a common inventive concept, could be searched without effort justifying an additional fee.

# INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 01/23681

Patent document cited in search report		Publication date		Patent family member(s)		Publication date
US 5334463	A	02-08-1994	JP	2989353 B2		13-12-1999
			JP	5151983 A		18-06-1993
DE 19810468	A	16-09-1999	DE	19810468 A1		16-09-1999
			WO	9946845 A1		16-09-1999
			EP	1062716 A1		27-12-2000
			JP	2002507049 T		05-03-2002
US 5714874	A	03-02-1998	FR	2709873 A1		17-03-1995
			DE	4431747 A1		09-03-1995
			GB	2281642 A , B		08-03-1995
			JP	7153474 A		16-06-1995
US 5734258	A	31-03-1998	NONE			

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